Noise reduction

The invention relates to a method and a device, in which noise filtering is applied. The invention further applies to a video system.

There is presently an increasing interest in digital transmission of image
5    sequences, e.g. through the Internet. Especially in the consumer electronics area, the sources of these images, such as video-cameras, video recorders, satellite receivers and others are affected by various types of noise. In particular, in the case of CCD and CMOS cameras, the sensor noise is usually modeled as white Gaussian, whereas vertical or horizontal streaks may be found in video scanned from motion picture films or played by a video recorder,
10   respectively. Before storage and/or transmission, it is advisable to reduce the noise level in the images, both to improve the visual appearance and to reduce the bit rate. Various algorithms are known from the art for the attenuation of noise having different distributions, which are generally very complex and consequently not amenable to real time implementation in consumer equipment, or provide poor performance, typically introducing
15   artifacts and smoothing edges.

An object of the invention is to provide less complex noise reduction. To this end, the invention provides a method of and a device for noise filtering and a video system as defined in the independent claims. Advantageous embodiments are defined in the dependent
20   claims.

In a first embodiment of the invention, a type of noise in the signal is estimated, and one of at least two noise filters is enabled, the enabled noise filter being a most suitable filter for the estimated type of noise. The invention is based on the insight that estimating a type of noise and automatically enabling one filter out of a set of simple filters,
25   each favorable to a specific noise type, is more effective than a complex filter which has to cope with different noise characteristics. Both the noise type estimation and the filters have a low complexity and are amenable for low-cost applications.

Edge preserving noise reduction can be achieved using spatio-temporal rational and median based filters. A rational filter is a filter described by a rational function,

e.g. the ratio of two polynomials in input variables. It is well known that spatio-temporal rational filters can effectively distinguish between details and homogeneous regions by modulating their overall low-pass behavior according to the differences of suitably chosen pixels [1], so that noise is significantly reduced while details are not blurred. They are

5    effective on various types of noise, including Gaussian noise [1] and contaminated Gaussian noise [2]. Contaminated Gaussian noise has a probability distribution according to:

$$v \sim (1 - \lambda)N(\sigma_n) + \lambda N(\frac{\sigma_n}{\lambda}) \quad (1)$$

wherein $\lambda$ is a parameter and $N(\sigma)$ is a Gaussian distribution with variance $\sigma$. A variance of the contaminated Gaussian distribution is given by: $\sigma_v^2 = \sigma_n^2(1 - \lambda + 1/\lambda)$    (2)

10   In case of long-tailed noise, a simple median filter [3] is used, which is effective both for single noisy pixels and for horizontal and vertical streaks, so that there is no need to distinguish between ideal and real impulsive noise. Median based operators are very efficient in case of long-tailed noise, especially impulsive noise, while their use in case of Gaussian noise is not advisable, because they tend to generate streaking and blotching artifacts.

15         A further embodiment of the invention uses a simple algorithm to estimate the type of noise in the image sequence. This embodiment uses a kurtosis of the noise as a metric for the type of noise. The kurtosis is defined as [4]:

$$k = \mu_4 / \sigma^4 \quad (3)$$

wherein $\mu_4$ is a fourth central moment of the data and $\sigma$ is a variance of the data in the image

20   sequence. The fourth central moment is given by $\mu_4 = E(x - \bar{x})^4$    (4) wherein $E$ is an expectation of a variable and $E(x) = \bar{x}$. The fourth central moment $\mu_4$ is related to the peakedness of a single-peaked distribution. The kurtosis is dimensionless with $k$ = 3 for a Gaussian distribution. A kurtosis value of 3 therefore means that the noise distribution has, in some sense, a same degree of peakedness as a member of the normal

25   family. Further, $k > 3$ for contaminated Gaussian noise, and $k >> 3$ for impulsive noise.

Prior art operators which are able to distinguish among several types of noise are very complex. For example, in [5] a block-based, non-linear filtering technique based on Singular Value Decomposition that employs an efficient method of estimating noise power from input data is presented, however, an hypothesis of additive noise is required and only

30   Gaussian distributions are used. In [6], in order to detect and estimate both deterministic and random Gaussian signals in non-Gaussian noise, the covariance of the latter is determined using higher order cumulants. The inverse problem is treated in [7], where signal detection

and classification in the presence of additive Gaussian noise is performed using higher order statistics.

The input signal $x$ is formed by an original noise-free signal $y$ and a noise signal $n$ according to: $x = y + n$. In a further embodiment of the invention, the noise $n$ is approximated by computing a difference between the signal $x$ and the same signal being noise filtered, preferably in a median filter [8]. A median of N numerical values is found by taking a middle value in an array of the N numerical values sorted in increasing order. A median filter may also be referred to as a non-linear shot noise filter, which maintains high frequencies. Due to the well-known noise reduction and edge preserving properties of the median filter, the resulting signal, $z = x - median(x)$, is composed approximately of noise only, i.e. $z \cong n$. The kurtosis $k$ is then estimated on $z$ to provide an indication of the type of noise. Although $z$ does not coincide with the original noise $n$, for reasonable values of the noise variance (in case of Gaussian noise or contaminated Gaussian noise) or of a percentage of noisy pixels (in case of impulsive noise), the parameter $k$ allows to correctly discriminate the types of noise, using two suitable thresholds. There is no overlap in values of the parameter $k$ for Gaussian, contaminated Gaussian and long-tailed noise, so that it is actually possible to correctly discriminate the various noise types using two thresholds, being 6 and 15.

Preferably, because the noise is supposed to be spatially uniform, a small part of each image (e.g. 3 by 3 pixels sub-image) is analyzed, in order to keep the computational load per image low. Because a stable estimate is needed, an analysis is preferably performed by cumulating data for a plurality of images before actually computing $k$. An estimate over 900 pixels (i.e. over 100 frames) has a reasonable low variance.

The aforementioned and other aspects of the invention will be apparent from and elucidated with reference to the embodiments described hereinafter.

In the drawings:

Fig. 1 shows an embodiment of a video system according to the invention;

Figs. 2A...2D show exemplary spatial directions considered in the filters: Fig. 2A: horizontal, Fig. 2B: vertical, Fig. 2C and Fig. 2D: diagonal;

Fig. 3 shows an exemplary direction used by a temporal part of a rational filter for Gaussian noise; and

Fig. 4 shows an exemplary combination of directions used by a temporal part of a rational filter for contaminated Gaussian noise.

The drawings only show those elements that are necessary to understand the invention.

Fig. 1 shows an embodiment of a video system 1 according to the invention. The video system 1 comprises an input unit 2, such as a camera or an antenna, for obtaining an image sequence $x$. The video system 1 further comprises a noise filter 3. The noise filter 3 comprises a noise discriminator 30 for estimating a type of noise in the image sequence x. The noise discriminator 30 controls a set of filters 31. Depending on the estimated type of noise, a most suitable filter in the set of filters 31 is enabled.

The noise discriminator 30 comprises a median filter 301, a subtractor 302 and a noise type estimator 303. The median filter 301 filters the input signal $x$ to obtain a filtered version of $x$, being *median(x)*. The filtered signal *median(x)* is subtracted from the input signal x, resulting in an approximation of the noise $n$ in the input signal $x$, the approximation given by: $z = x - median(x)$. The signal $z$ is furnished to the noise estimator 303 for estimating the type of noise. As described above, the estimator 303 applies a kurtosis $k$ on the noise signal $z$. The estimator 303 furnishes a kurtosis (noise type) depending control signal to the set of filters 31. Depending on the control signal from the estimator 303, one of the filters in the set 31 is enabled. The output $y$ of the noise filter 3 may be transmitted to a receiver or stored on a storage medium.

In a preferred embodiment, the set of filters 31 comprises three different filters 310, 311, 312 in order to be able to treat different types of noise. Their operation is automatically controlled by the noise discriminator 30 as described above. Preferably, their support is restricted to two temporally adjacent images only, to keep the computational complexity low. The use of only two images has the further advantage that the amount of required image memory is lower than in methods that use more images. In this embodiment, the filter 310 is suitable for Gaussian noise, the filter 311 is suitable for contaminated Gaussian noise, and the filter 312 is suitable for long-tailed noise.

The filters for the Gaussian noise and the contaminated Gaussian noise 310, 311 are preferably spatio-temporal rational filters having a similar structure, constituted by the sum of a spatial and a temporal filtering part. Each filter output $y_0$ is computed as:

$$y_0 = x_0 - f_{spatial} - f_{temp} \qquad (5)$$

with
$$f_{spatial} = \sum_{i,j \in I} \frac{-x_i + 2x_0 - x_j}{k_s(x_i - x_j)^2 + A_s} \qquad (6)$$

where $x_0$, $x_i$ and $x_j$ are pixel values within a mask ($x_0$ being the central one), $i, j \in I$ describe a set of spatial filtering directions shown in Figs. 2A...2D, and $k_s$ and $A_s$ are suitable filter parameters. The temporal filtering part, $f_{temp}$ has a similar form, although $f_{temp}$ operates also on pixels of a previous image, and is described below. It may be seen that the spatial filter is able to distinguish between homogeneous and detailed regions, in order to reduce noise while maintaining the image details. In fact, if the mask lies in a homogeneous region, the pixel differences $(x_i - x_j)^2$ which appear at the denominator are small, and the high-pass component present at the numerator, which is subtracted from $x_0$, gives an overall low-pass behavior. In turn, if the same differences have a large value, an edge is supposed to be present, and the filter leaves the pixel unchanged in order not to blur the detail.

The temporal part exploits the same principle of detail sensitive behavior, and for Gaussian noise the form is similar to that of the spatial part:

$$f_{temp}^{(gauss)} = \sum_{i \in J} \frac{- x_i^p + x_0}{k_{t1}(x_i^p - x_0)^2 + A_{t1}} \qquad (7)$$

where $i \in J$ describes a set of temporal filtering directions as shown in Fig. 3. In Fig. 3 only one of 9 possible directions (according to the possible positions of $x_i^p$) has been drawn for the sake of clarity. The superscript $p$ refers to pixels belonging to a previous image, and $k_{t1}$ and $A_{t1}$ are suitable filter parameters.

The situation is slightly more complicated for contaminated Gaussian noise. In this case, details and noise are more difficult to discriminate, because the pixel noise level can be large (due to the rather long tails of the distribution), and less information with respect to the spatial case is available; more precisely, due to the limited temporal size of the filter support (only two images), pixels are available only at one (temporal) side of $x_0$ (vice-versa, in the spatial part of the filter 311, pixels both at the right and at the left of $x_0$, or both on top of and below, are available) so that the simple denominator of the spatial part does not allow to distinguish between a single noisy pixel and the edge of an object. For contaminated Gaussian noise, $f_{temp}$ is defined as:

$$f_{temp}^{cont.Gauss} = \sum_{i \in J} \frac{- x_i^p + x_0}{[k_{t2}(x_i^p - x_0)^2 + k_{t3}(x_i^p - x_i)^2]/2 + A_{t2}} \qquad (8)$$

where $i \in J$ describes a set of temporal filtering combinations (a combination of a temporal direction with a spatial direction) as shown in Fig. 4 and where $k_{t2}$, $k_{t3}$ and $A_{t2}$ are suitable filter parameters. In Fig. 4 only one combination of $x_i^p$ and $x_i$ of a plurality of possible combinations has been drawn for the sake of clarity. In this case, the pixels at the denominator, which controls the strength of the low-pass action, are three instead of two: $x_i$,

$x_i^P$ and $x_0$. In fact, as already mentioned above, it is not advisable to use the same control strategy as for Gaussian noise: the difference $(x_i^P\text{-}x_0)$ may be large due to a noise peak instead of an edge with consequent loss of the noise filtering action. In turn, if the same difference is corrected by averaging with another difference, i.e. $(x_i^P\text{-}x_i)$, the denominator remains low also in presence of isolated noisy pixels, and the desired low-pass behavior is obtained.

5

Although the filters 310 and 311 are shown in Fig. 1 as separate filters, in a practical embodiment, the filters 310 and 311 are combined in one rational filter with a common spatial part and different temporal parts, a first temporal part for Gaussian noise and a second temporal part for contaminated Gaussian noise. Depending on the type of noise

10 estimated in the noise discriminator 30, the suitable temporal part is enabled. In a further practical embodiment, the first temporal part and the second temporal part are implemented as one temporal filtering part according to equation (8), wherein in case the noise has a Gaussian distribution, the parameter $k_{t3}$ is taken zero to obtain a rational filter according to equation (7).

15

The rational filter 310/311 is enabled if the value of the kurtosis $k$ of $z$ is lower than 15, otherwise the median filter 312 is enabled. If the kurtosis $k$ is lower than 6, the first temporal part (for the Gaussian noise) is enabled. If the kurtosis $k$ is between 6 and 15, the second temporal part (for the contaminated Gaussian noise) is enabled.

In order to treat long-tail noise effectively, the filter 312 is preferably a simple

20 median filter. In general, a median filter is based on order statistics. A two-dimensional median filter is given by:

$$y_0 = median\{x_i, x_0, x_j\} \qquad (9)$$

The set $x_i$, $x_j$ defines a neighborhood of the central pixel $x_0$ and is called a filter mask. The median filter replaces the value of the central pixel by the median of the values of the pixels

25 in the filter mask. A simple mask, which is appropriate, is a 5 element X-shaped filter. Such a filter is known from [3]. In case of the 5 element X-shaped filter, the filter mask includes the central pixel $x_0$ and the pixels diagonally related to the central pixel $x_0$. These spatial directions are indicated in Figs. 2C...D.

Preferably, both ideal impulsive noise (single noisy pixels), and real world

30 impulsive-like noise (e.g. present in satellite receivers) made of horizontal one pixel wide strips rather than by single noisy pixels, are removed. Both types of noise affect only one pixel out of 5 in the X-shaped mask, so that the noisy element is easily removed by the median operator. It is noticed, that one pixel wide vertical strips, which may be found in video obtained from motion picture films, can also be effectively removed by this filter.

To remove wider strips, a larger support is required. Once impulsive noise type has been detected, the simple median is used.

The noise discriminator 30 controls the set of filters 31. Although in the above-described embodiments, hard switching is used, soft switching is also possible, e.g.
5     enabling the most suitable filter of the set of filters 31 by more than 50 % and in addition partly enabling one or more of the other filters in the set of filters 31. In an exemplary case in which the signal includes mostly Gaussian noise, the filter 310 may be enabled for 80% and the other two filters 311 and 312 for 10%. The claims should be construed as comprising such a soft switching implementation too.

10     Depending on the application or the image sequence, other filters or a different noise discriminator may be used. The basic idea of the invention is to use at least two filters, designed for different types of noise, and a noise discriminator for enabling the most suitable filter of the at least two filters. The invention is also applicable to other signals, e.g. audio.

Motion-compensated based algorithms generally provide better performances
15     at the cost of a much more complex structure. Motion-compensated based algorithms are preferably applied in professional embodiments of the invention.

It should be noted that the above-mentioned embodiments illustrate rather than limit the invention, and that those skilled in the art will be able to design many alternative
20     embodiments without departing from the scope of the appended claims. The word 'image' also refers to picture, frame, field, etc. In the claims, any reference signs placed between parentheses shall not be construed as limiting the claim. The word 'comprising' does not exclude the presence of other elements or steps than those listed in a claim. The invention can be implemented by means of hardware comprising several distinct elements, and by means of
25     a suitably programmed computer. In a device claim enumerating several means, several of these means can be embodied by one and the same item of hardware. The mere fact that certain measures are recited in mutually different dependent claims does not indicate that a combination of these measures cannot be used to advantage.

In summary, the invention provides noise filtering of a signal by estimating a
30     type of noise in the signal and enabling one of at least two noise filters, the enabled noise filter being a most suitable filter for the estimated type of noise. An approximation of the noise in the signal is obtained by computing a difference between the signal and a noise-filtered version of the signal. The invention uses a kurtosis of the noise as a metric for estimating the type of noise. If the estimated type of noise is long-tailed noise, a median filter

is enabled to filter the signal. If the estimated type of noise is Gaussian noise or contaminated Gaussian noise, a spatio-temporal filter is enabled to filter the signal. The invention may be applied in a video system with a camera and a noise filter.

References:

[1]        G. Ramponi, 'The rational filter for image smoothing', *IEEE Signal Processing Letters*, vol. 3, no. 3, March 1996, pp. 63-65

5

[2]        F. Cocchia, S. Carrato and G. Ramponi, 'Design and real-time implementation of a 3-D rational filter for edge preserving smoothing', IEEE Trans. on Consumer Electronics, vol. 43, no. 4, Nov. 1997, pp. 1291-1300

10    [3]        I. Pitas and A.N. Venetsanopoulos, *Non-linear digital filters*, Kluwer Academic Publishers, Boston MA(USA), 1990, pp. 63-115

[4]        E. Lloyd, *Handbook of applicable mathematics*, John Wiley & Sons Ltd., New York, 980, pp. 155-160

15

[5]        K. Konstantinides, B. Natarajan and G.S. Yovanof, 'Noise estimation and filtering using block-based singular value decomposition', *IEEE Trans. on Image Processing*, vol. 6, no. 3, March, 1997, pp. 479-483

20    [6]        B.M. Sadler, G.B. Giannakis and K-S Lii, 'Estimation and detection in nonGaussian noise uding higher order statistics', *IEEE Trans. on Signal Processing*, vol. 42, no. 10, Oct. 1994, pp. 2729-2741

[7]        G.B. Giannakis and M.K. Tsatsanis, 'Signal detection and classification using
25    matched filtering and higher order statistics', IEEE Trans. on Acoust., Speech and Signal Processing, vol. 38, no. 7, July 1990, pp. 1284-1296

[8]        S.I. Olsen, 'Estimation of noise in images: an evaluation', *CVGIP*, vol. 55, no. 4, July 1993, pp. 319-323